Effect of cosmic rays on the resonant gravitational wave detector NAUTILUS at temperature T=1.5 K

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Abstract

The interaction between cosmic rays and the gravitational wave bar detector NAUTILUS is experimentally studied with the aluminum bar at temperature of T=1.5 K. The results are compared with those obtained in the previous runs when the bar was at T=0.14 K. The results of the run at T = 1.5 K are in agreement with the thermo-acoustic model; no large signals at unexpected rate are noticed, unlike the data taken in the run at T = 0.14 K. The observations suggest a larger efficiency in the mechanism of conversion of the particle energy into vibrational mode energy when the aluminum bar is in the superconductive status.

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The gravitational wave (GW) detector NAUTILUS recently recorded signals due to the passage of cosmic rays (CRs) [1, 2, 3]. Several authors [4]-[11] estimated the possible acoustic effects due to the passage of particles in a metallic bar. The mechanism adopted assumes that the mechanical vibrations originate from local thermal expansion caused by warming up due to the energy lost by the particles crossing the material. It was predicted that for the vibrational energy in the longitudinal fundamental mode of a metallic bar the following formula would hold:

$$E = \frac{4}{9\pi}\frac{\gamma^2}{\rho L v^2}\left(\frac{\mathrm{d}W}{\mathrm{d}x}\right)^2\left(sin\left(\frac{\pi z_0}{L}\right)\frac{sin(\pi l_0 cos(\theta_0)/2L)}{\pi R cos(\theta_0)/L}\right)^2 \tag{1}$$

where L is the bar length, R the bar radius, l_0 the length of the particle's track inside the bar, z_0 the distance of the track midpoint from one end of the bar, θ_0 the angle between the particle track and the axis of the bar, E the energy of the excited vibration mode, dW/dx the energy loss of the particle in the bar, ρ the density, v the sound velocity in the material and γ is the Gr$\ddot{u}$neisen coefficient (depending on the ratio of the material thermal expansion coefficient to the specific heat) which is considered constant with temperature.

The resonant-mass GW detector NAUTILUS [12], operating at the INFN Frascati Laboratory, consists of an aluminum alloy 2300-kg bar which can be cooled to very low temperatures, of the order of 0.1 K, below the superconducting transition temperature of this alloy, $T_C = 0.92$ K [13]. The bar is equipped with a capacitive resonant transducer, providing the read-out. Bar and transducer form a

coupled oscillator system with two resonant modes, whose frequencies are 906.4 Hz and 922.0 Hz. The transducer converts the mechanical vibrations into an electrical signal and is followed by a dcSQUID electronic amplifier. The NAUTILUS data, recorded with a sampling time of 4.54 ms, are processed with a filter [14] optimized to detect pulse signals applied to the bar, such as those due to a short burst of GW.

NAUTILUS is equipped with a CR detector system consisting of seven layers of streamer tubes for a total of 116 counters [16]. Three superimposed layers, each with an area of $36\mathrm{m}^2$, are located over the cryostat (top detector). Four superimposed layers are set under the cryostat, each with an area of $16.5\mathrm{m}^2$ (bottom detector). Each counter measures the charge, which is proportional to the number of particles. The CR detector is able to measure particle density up to 5000 par./m^2 without large saturation effects and gives a rate of showers in good agreement with the expected number [16, 17], as verified by measuring the particle density in the top detector, which is not affected by the interaction in the NAUTILUS bar.
In a previous paper we reported the results of a search for correlation between the NAUTILUS data and the data of the CR detector, when for the first time acoustic signals generated by CR showers were measured [1]. In a further investigation, we found very large NAUTILUS signals at a rate much greater than expected [2, 3]. (We notice that a GW bar detector, used as particle detector, has characteristics very different from the usual particle detectors which are sensitive only to ionization losses.) Since the bar temperature was about 0.14 K, i.e. the aluminum alloy was superconductor, one could consider some unexpected behaviour due to the transition to the normal state along the particle trajectories. These effects were estimated [7, 8] for type I superconductor (as aluminum). They are very small and cannot account for our observations, if the showers include only electromagnetic and hadronic particles.

In the present paper, the results of the effect of the CR passage on NAUTILUS during the years 2000 and 2001 are reported together with comparison with the previous observations. During this period NAUTILUS operated at different thermodynamic temperatures. In 2000, until July, the NAUTILUS bar cryogenic temperature was 0.14 K; then, between August and December, it was brought at 1.1 K. In the period 1 March 2001 through 30 September 2001 NAUTILUS operated at a temperature of 1.5 K. We proceeded to apply to these data the same data analysis algorithms used for the previous runs: coincidence search [2, 3] and zero threshold search [1], latter being more efficient for detecting small amplitude signals.

$Coincidence\ search$.- The event list employed in the analysis was generated by considering only the time periods with noise temperature (expressing the minimum detectable innovation) less than 5 mK, and imposing the amplitude threshold at $\mathrm{SNR} = 4.4$ on the data filtered with an algorithm matched to detect short bursts. The threshold value was established trough IGEC Collaboration [15] for data exchange among the GW groups to search for coincident events. For each threshold crossing we take the maximum value and its time of occurrence. These two quantities define the event of the GW detector. The CR shower list was generated by considering those events giving a particle density ≥ 300 par./m^2 in the bottom detector. Comparing the two lists, we searched for coincidence in a window of ± 0.1 s centered at CR arrival time. The expected number of accidental coincidences was experimentally estimated, by means of the time shifting algorithm [18, 19]. By shifting the events time in one of the two data sets by an amount δt the number of coincidence $n(\delta t)$ is determinated. Repeating for N different values of the time delay, the expected number of coincidence is $\bar{n} = \frac{1}{N-1}\sum n(\delta t)$. With these criteria, i.e. the temperature noise less than 5 mK, the coincidence time window of ± 0.1 s, and the particle density showers larger than 300 par./m^2, we found, with NAUTILUS temperature at 0.14 K, 12 coincident events on 1998 and 9 coincident events during Feb-Jul 2000. For both periods, the energy values of the events are concentrated in the 0.1 K range. For the remaining part of 2000, with NAUTILUS temperature at 1.1 K, we found no coincident event. In 2001, with NAUTILUS bar temperature at 1.5 K, we found just one coincidence.

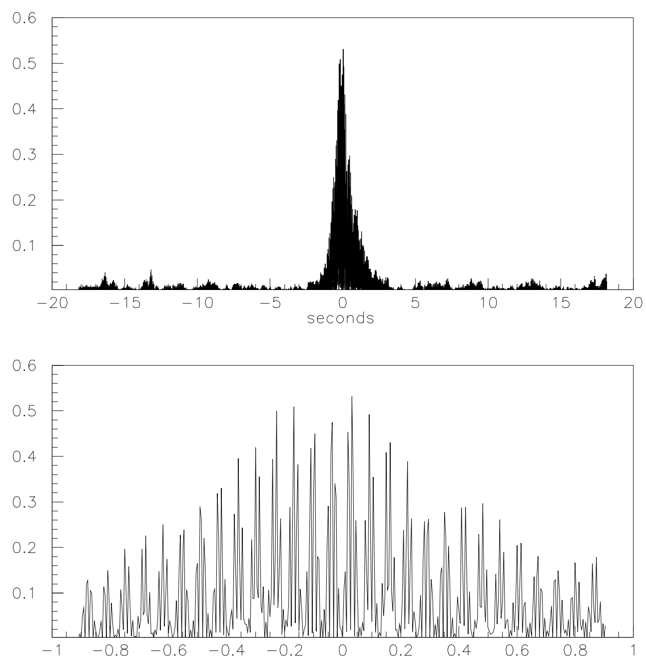

Fig. 1: The NAUTILUS response to the CR shower with particle density 2812 par./m^2, filtered energy (K) versus time (s), centered at the CR shower arrival time. The lower figure is a zoom of the upper one. We note the oscillation related to the beating of the two resonant modes and the decay due to the detector bandwidth, $\delta f \sim 0.4$ Hz.

We report the result of the analysis and comparison in Table 1. This table affords evidence at about $4\ \sigma$ level that the observed coincidence rate is related to the bar temperature. In 2001, the single coincidence event had high NAUTILUS energy, $E \sim\ 0.5$ K, and very large particle density $M = 2812$ par./m^2 in the bottom detector. The response to this CR shower is shown in Fig.1, filtered energy versus time centered at the CR shower arrival time.
This is the typical response expected for a delta-like excitation acting on the bar. To estimate the energy absorbed by the incoming CR shower, we apply eq.1 to the case of NAUTILUS:

$$E = 7.64\ 10^{-9}\ W^2\ f \tag{2}$$

where E is expressed in kelvin units, W in GeV units is the energy delivered by the particle to the bar and f is a geometrical factor of the order of unity.

We get for this event $W\ \sim\ 8$TeV. From the data shown in reference [2] (our calculations and experimental data from the CASCADE collaboration) we expect in 83.5 days of NAUTILUS data taking about one event with energy greater than 0.1 K due to the hadrons, able to deliver to the GW detector an energy of a few TeV.

$Zero\ threshold\ search.$- Again we used these data when NAUTILUS noise temperature was less than 5 mK and the shower multiplicity was larger than 300 par./m^2 in the bottom CR detector. In correspondence with each CR shower we considered the NAUTILUS filtered data in a time period of ± 19 s centered at the CR arrival time. With this selection, in 2000, there were 308 data stretches corresponding to as many CR showers during a total period of observation of 707 non continuous hours. The selected stretches were superimposed and averaged at the same relative time with respect to the arrival time of the CR showers. The result of this procedure is shown in Fig.2, where we plot the averages for each data sample (136.3 ms) versus time, for the 308 CR events with particle density greater than 300 par./m^2, graph(a). Several events with energy of the order of 0.1 K contribute to the large response at zero time, which confirms the results obtained by the data recorded during 1998 [1]. On the same figure, on graph (b), we report the result of the same analysis applied to the 968 stretches data of the year 2001, with the

Table 1: Coincidences during the years 1998, 2000 and 2001, using a coincidence window of ± 0.1 s. NAUTILUS temperature, duration of the analysis period, expected number of accidental coincidences $\bar{n}$ and number of coincidences n_c.

time period	NAUTILUS temperature (K)	duration hours	n_c	$\bar{n}$	rate (ev/day)
Sep-Dec 1998	0.14	2002	12	0.47	
Feb-Jul 2000	0.14	707	9	0.42	
Total		2709	21	0.89	0.178 ± 0.041
Aug-Dec 2000	1.1	118	0	0.03	
Mar-Sep 2001	1.5	2003	1	0.42	
Total		2121	1	0.45	0.006 ± 0.011

aluminum bar cooled to 1.5 K. The major contribution to the signal at zero time is due to the single event of Fig.1. Removing from the data set that event, we obtain graph (c). Comparison shows clearly the different response of NAUTILUS in the two time periods.

The question arises whether NAUTILUS, operating at temperature T=1.5 K (in a normal non superconductive status) is sensitive to the CR showers as predicted by the thermo-acoustic models. For a quantitative estimation of a possible effect due to CR we proceeded as follows. We consider NAUTILUS stretches for the year 2001 corresponding to CR in various contiguous multiplicity intervals. For the stretches of each of the selected multiplicity intervals we calculate the energy averages over thirty contiguous sampling times corresponding to 136.3 ms. At zero delay we take the average at time 0 ± 68.2 ms. We recall that the beat period in the filtered signal, due to the two resonance modes, is 64 ms, as we can see from Fig.1. With this averaging procedure we avoid the problem of taking either a maximum value or a minimum value, which are not exactly in phase among the various stretches. By doing so we get an average value smaller than the maximum by a factor 3.6, as we find by numerically averaging the data of Fig.1. For each multiplicity range, the measured signal (average at time 0 ± 68.2 ms) is compared with the signal we expect due to the electromagnetic component of the shower. The theoretical value is given by [2]

$$E_{th} = \Lambda^2 \cdot 4.7\ 10^{-10}\ K \tag{3}$$

where Λ is the number of secondaries through the bar. The measured multiplicity might be affected by a systematic error of the order of $\pm 25\%$ [2]. As an estimate of the background we take the average energy during the periods from - 4000 to - 3000 sampling times (from - 18.18 s to - 13.63 s) and from 3000 to 4000 samplings times (from 13.63 s to 18.18 s), for a total time period of 2000 sampling times, 9.088 seconds.

In Fig. 3 we show the difference in mK units between the average energy at zero time delay and the background versus the expected signal due to the electromagnetic component of the CR showers. The straight line is a least square fit through the origin and the vertical bars indicate statistical errors ($\pm$ one standard deviation). The χ^2 calculated for a null hypothesis (signal=background) gives $\chi^2 = 42.4$ with 9 degrees of freedom for a probability of $2.8\ 10^{-6}$. The slope of the straight line has value 0.85 ± 0.13. If we take into account the systematic error on the experimental value of Λ ($\sim \pm 25\%$) and the error on the calibration of the NAUTILUS event energy, of the order of 10%, we get for the slope $0.85 \pm 0.16 \pm 0.42$, showing a good agreement with the thermo-acoustic model. The χ^2 calculated for the hypothesis that the individual data be along the straight line is $\chi^2 = 13.3$ for a probability of 0.10.

$Conclusions$. Comparing the previous and the present measurements, two different behaviours of the aluminum bar detector are noticed, with evidence at 4 σ level.

In the run with the bar temperature above the superconductive transition we find a result in good agreement with the theoretical predictions of the thermo-acoustic model. These measurements are a record for the GW detectors, as signals of the order of 10^{-4} K, corresponding to 10^{-8} eV, were extracted from noise. The unexpected behaviour of NAUTILUS noticed in the previous runs [2, 3], i.e. very large signals

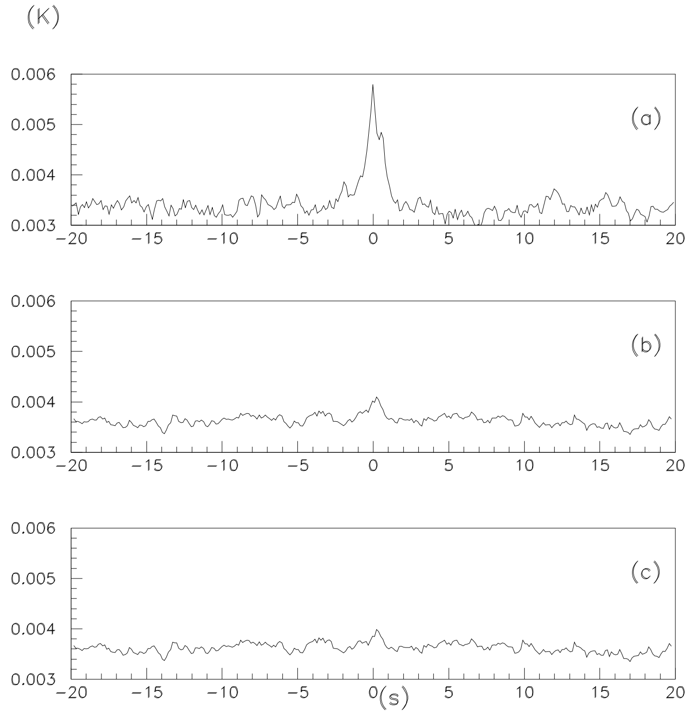

Fig. 2: The energy response of NAUTILUS to the CRs passage at zero time. In fig.(a), we show the average energy (K) vs time for 308 data stretches detected during 2000, with NAUTILUS bar temperature at 0.14 K. In fig.(b), the result of the same analysis is shown for 968 data stretches detected during 2001, with bar temperature at 1.5 K. The CR showers particle density is larger than $300\frac{particles}{m^2}$ for the both periods. Excluding from the last data set the event of Fig.1, the average energy for 967 data stretches is shown in the fig.(c).

Table 2: The average NAUTILUS signal $\mathrm{E_{obs}}$, and its standard deviation, vs the multiplicity of CR events. multiplicity selections. Also indicated are the number of stretches for each selection and the difference between the signal at zero delay and the background, with its standard deviation. The theoretical values are calculated with eq.3, (valid for the electromagnetic component of the shower) divided by 3.6, using the measured particle density in the lower part of CR detector and taking the average. The big event of Fig.1 has been excluded from the last row.

$\frac{\mathrm{particles}}{\mathrm{m}^2}$	number of stretches	E_{obs} mK	$\sigma_{E_{obs}}$ mK	$E_{obs} - bkg$ mK	$\sigma_{E_{obs}-bkg}$ mK	E_{th} mK
300 - 600	688	3.690	0.085	0.310	0.085	0.069
600 - 900	138	3.67	0.21	0.20	0.21	0.228
900 - 1200	63	3.91	0.37	0.40	0.37	0.453
1200 - 1500	34	4.10	0.26	0.98	0.26	0.783
1500 - 1800	16	3.35	0.77	-0.24	0.79	1.119
1800 - 2100	9	4.76	0.80	0.91	0.84	1.517
2100 - 2400	11	4.75	0.58	1.82	0.60	2.200
2400 - 2700	3	4.4	1.2	1.3	1.4	2.744
2700 - 3000	5	6.2	1.6	2.5	1.7	3.478

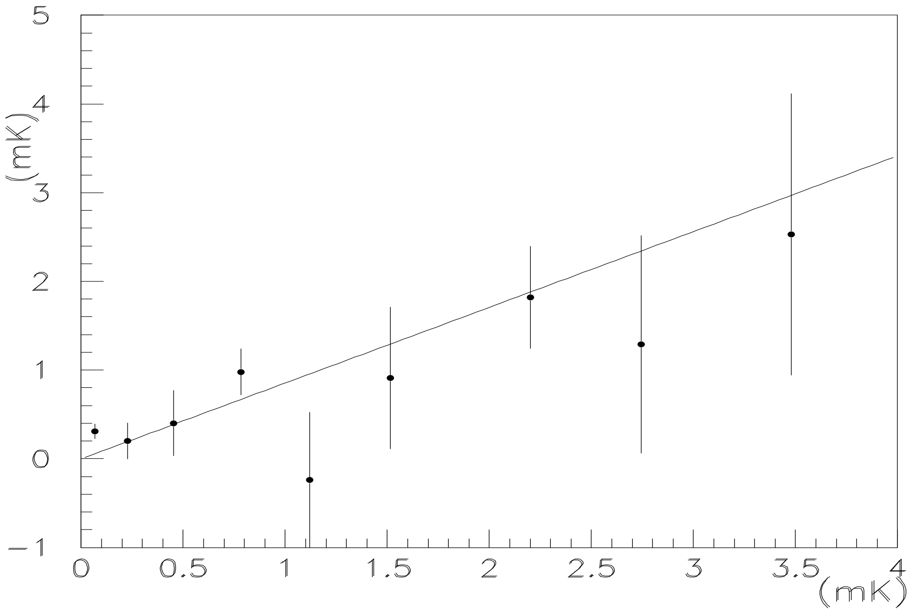

Fig. 3: Experimental signal versus the expected signal due to the electromagnetic component of the CR shower (see text and Table 2). The straight line is at least square fit and the vertical bars indicate statistical errors ($\pm$ one standard deviation).

at a rate higher than expected, occurs only at ultracryogenic temperatures. The observed phenomenology suggests a larger efficiency in the mechanism of conversion of the particles energy into the vibrational mode energy, at least for some type of particles, when the aluminum bar is in the superconductive status.

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